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Assessment of deterministic PMF modelling approaches

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Abstract

Probable maximum flood (PMF) event estimation has challenged the scientific community for many years. Although the concept of the PMF is often applied, there is no consensus on the methods that should be applied to estimate it. In PMF estimation, the spatio-temporal representation of the probable maximum precipitation (PMP) as well as the choice of modelling approach is often not theoretically founded. Moreover, it is not clear how these choices influence PMF estimation itself. In this study, combinations of three different spatio-temporal PMP representations and three different modelling approaches are applied to determine the PMF of a mesoscale basin keeping the antecedent catchment conditions and the total precipitation amount constant. The nine resulting PMF estimations are used to evaluate each combination of methods. The results show that basic methods allow for a rough estimation of the PMF. In cases where a physically plausible and reliable estimation is required, sophisticated PMP and PMF estimation approaches are recommended.

Keywords: PMP, PMF, extreme flood, flood modelling, model assessment

1. INTRODUCTION

Estimations of the probable maximum flood (PMF) are commonly required by planners dealing with sensitive infrastructure, such as nuclear power plants or hydropower dams, and are also of increasing importance to insurance and reinsurance providers. Engineers and catastrophe modellers regularly rely on PMF estimations, and their results are considered important parameters for worst-case assessments. The concept and the definition of the PMF are therefore widely used. However, various approaches with considerable methodological differences are used for its calculation.

The estimation of a PMF is based on the estimation of a site-specific probable maximum precipitation (PMP), which is generally calculated following World Meteorological Organization (WMO) guidelines (WMO 1986, WMO 2009). Then, the reaction of the catchment to the PMP input is deterministically modelled. The hydrograph or the peak discharge modelled in this procedure is considered to be the PMF. Although the concept of PMP/PMF has been critically discussed (Papalexiou and Koutsoyiannis 2006, Papalexiou et al. 2013, Salas et al. 2014, Micovic et al. 2015, Rouhani and Leconte 2016), this general procedure of deterministic PMF estimation is widely accepted. Though there is consensus on the general procedure, scholars disagree on how the single steps of this procedure should be carried out. Two main discordances will be further discussed.

The first substantial discordance is on how precipitation is represented in space and time. Several spatio-temporal representations of the PMP have been applied in recent studies. The simplest representation assumes a uniform precipitation distribution over space and time. Kienzler et al. (2015) in addition to various engineers and practitioners estimate PMF using this representation. Although a uniform distribution of the PMP over space and time is straightforward and easily applicable, Seo et al. (2012) show that the use of this approach generally "*underestimates potential flood risk that could be exacerbated by rainstorm movement*". Such rainstorm movement can be accounted for by applying the so-called isohyetal or hyetograph method, which is described by the National Weather Service (1982) and Cudworth (1989). In the isohyetal method, elliptical standard storm patterns (isohyets) are created in a way that the catchment reaction in maximized. The method is applied in recent PMF studies by Beauchamp et al. (2013) and Castro-Bolinaga and Diplas (2014). The hyetograph method leads to results that come closer to observed precipitation patterns. Regarding the PMF, however, this method can still lead to the exclusion of unlikely but physically possible precipitation distributions. These can be accounted for by using a Monte

Carlo approach (Felder and Weingartner 2016), which increases the number and the variability of considered spatio-temporal distributions. The Monte Carlo approach incorporates physically plausible distributions, although some generated patterns may deviate from observed distributions and are rather unlikely to occur. Salas et al. (2014) recently applied such a Monte Carlo approach. The compilation of several recent studies illustrates that fundamentally varying methods are used for generating spatio-temporal PMP representations. However, most of them do not provide theoretical justification for the methods they apply and there is no knowledge on how the choice of the precipitation pattern influences the PMF estimation.

The second substantial discordance on PMF estimation has to do with how the PMF is determined from the site-specific PMP, specifically which model type and model complexity is required to derive a reliable PMF estimation. According to the World Meteorological Organisation (WMO), "*Given the extreme magnitude associated with PMP, it is often considered unnecessary to adopt complex models to describe the process for the estimation of the PMF*" (WMO 2009). However, this statement may rather be seen as a hypothesis than an assessment, as it ignores recent developments in modelling techniques and computation power that have allowed improved runoff routing and retention effect modelling. Recent PMF studies are based on various modelling approaches and model complexities. The most straightforward approach involves applying a transfer function that calculates runoff based on PMP, e.g. by using a Unit Hydrograph-based model, as applied by Cudworth (1989) and Felder and Weingartner (2016). Today, most of the PMF estimations in science and practice are calculated by applying a deterministic rainfall-runoff model (Beauchamp et al. 2013, Kienzler et al. 2015, Zeimetz et al. 2015, Yigzaw and Hossain 2016). The most promising, but also the most intensive approach in terms of labour and computation power involves coupling a deterministic rainfall-runoff model with a hydrodynamic model. The application of such a coupled model potentially increases PMF estimation reliability because it incorporates retention and inundation processes. Castro-Bolinaga and Diplas (2014) successfully apply this approach. As is the case when it comes to spatio-temporal PMP representation, the choice of model type and complexity for PMF estimation is often not theoretically founded, and the influence of the selection of the modelling approach on the resulting estimation is unclear.

Several main factors have to be considered when it comes to selecting an appropriate methodological approach for PMF estimation:

1. The aim of a PMF study determines the required level of detail. For example, a simple approach may be sufficient for a preliminary study where only an approximation of the PMF magnitude is needed. In contrast, a PMF study that aims to determine potentially affected areas for insurance purposes requires high spatial resolution and high reliability. It therefore calls for applying a sophisticated model.
2. The researcher's expertise can affect the choice of a PMF estimation approach. Researchers may tend to choose approaches, and particularly models, with which they are familiar.
3. The availability of temporal, monetary and computational resources is often strictly limited. In consequence, this limits the applicability of certain methods and models.
4. The availability of geospatial, hydrological and meteorological data is a crucial factor for the applicability of sophisticated methods and models. All data must be appropriate for the chosen PMF estimation approach and must fulfil its minimal requirements in terms of data quality, accessibility and temporal and spatial resolution.
5. The accessibility of information on concepts, methods and models is often limited. Emerging concepts, methods and models must be public and comprehensibly documented, which is not always the case.

This list is clearly not exhaustive, as there may be several more crucial factors that influence the choice of a PMF estimation approach. The choice of an appropriate PMF estimation approach, however, is basically a trade-off between these five aspects. The effects of these choices on the estimation itself are often neglected; it remains unclear how the application of different spatio-temporal PMP representations and modelling approaches influences PMF estimation. Gaining this understanding is of particular importance when it comes to relatively new and emerging modelling techniques, like the application of coupled hydrologic-hydrodynamic models.

The present study evaluates how various spatio-temporal PMP representations and modelling approaches influence PMF estimation. Depending on the purpose of a PMF estimation, highly sophisticated methods may not always be required. The aim of this study is therefore to assess whether or not the application of sophisticated PMF estimation approaches is always desirable. This assessment of various methods aims to inform the selection among spatio-temporal PMP representation approaches and PMF modelling techniques.

For this purpose, three different methods for representing PMP distribution over space and time are used to estimate PMF using three different modelling approaches. The catchment conditions as well as the total amount of event precipitation (cumulative PMP) are held constant. This results in nine independent PMF estimations that vary due only to the chosen spatio-temporal PMP representation and modelling approach.

2. STUDY AREA

The study area, shown in Fig. 1, is the Aare catchment south of Bern in central Switzerland. It is situated at the northern edge of the Swiss Alps and covers an area of about 3000 km^2. The catchment's mean elevation is 1600 m a.s.l., and it ranges from 4000 m a.s.l. at the alpine peaks in the most southern parts of the catchment down to 500 m a.s.l. at the catchment outflow in the most northern part of the catchment. The mean annual rainfall in the study area is about 1700 mm, of which approximately 400 mm are evaporated and 1300 mm are discharged. The highest observed peak discharge from the catchment is 620 m^3 s^{-1} (1918-2015), and the mean annual flood amounts to 360 m^3 s^{-1}. The southern parts of the catchment consist of mountainous areas. Four major streams drain these mountainous areas into two lakes (see Fig.1). The area that surrounds the lakes and the area downstream of the lower lake's outflow are relatively flat and contain widespread flood-prone areas. Due to the diversity of the landscape and the presence of lakes and widespread flood-prone areas in the study area is affected by numerous processes with various complexities, making it an ideal case for assessing the effect of model choice on PMF estimation.

Besides the physical characteristics of the catchment, the availability of knowledge and data support the choice of this study area. When it comes to meteorological and hydrological data, a relatively dense and well-established measuring network is available. The availability of highly resolved topographical data, namely a LIDAR-generated DTM with 0.5m resolution, allows for processes that occur during flood events to be included in modelling. Data are provided by the Swiss Federal Office of Environment (FOEN), the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) and the Bernese State Office for Water and Waste (AWA). The hydrology of the catchment is well documented in former studies and flood-event analyses (e.g. FOEN 2000, FOEN 2008, FOEN 2009, Wehren 2010, Roessler et al. 2014).

3. METHODS

The main methodological differences among PMF estimations involve the use of different spatio-temporal PMP representation techniques and PMF modelling approaches. In this study, three different precipitation distribution approaches and three different modelling approaches are applied; nine varying combinations of precipitation distribution and modelling approach are considered. For each combination of methods, the calculated highest peak discharge represents the combination's PMF estimate. While other spatio-temporal PMP representation techniques and modelling approaches exist than the ones tested here, the techniques and approaches used in this study were selected because they represent fundamentally different techniques that are either frequently used in practice or emerging in science.

3.1 Spatio-temporal PMP distributions

This study relies on Grebner and Roesch's (1998) summer PMP estimation, which was calculated using WMO (1986) guidelines. The method applied by Grebner and Roesch (1998) corresponds to the indirect watershed approach described by WMO (2009). Based on Felder and Weingartner (2016), the estimated summer PMP depth used in this study amounts to approximately 300 mm for a 72 h event over 3000 km^2. This PMP amount is distributed over space and time, using three varying distribution approaches that have been applied in recent studies. An example of each of these spatio-temporal PMP distributions is shown in Fig. 2.

The simplest case of precipitation distribution is a uniform distribution over space and time. In this case, the estimated PMP of 300 mm was divided into 72 equal hourly amounts of 4.16 mm. These hourly amounts were then distributed uniformly over the catchment. Testing a uniform precipitation distribution makes it possible to assess the relative influence of the spatio-temporal precipitation distribution on PMF estimation in a comparative manner. This method is commonly applied by practitioners as well as scientists (e.g. Zeimetz et al. 2015).

The second precipitation distribution approach considered in this study is the hyetograph method. This method is suggested by WMO (2009) and has been applied in various case studies (e.g. Beauchamp et al. 2013, Castro-Bolinaga and Diplas 2014). The hyetograph method aims to produce idealized storm patterns and storm motions based on observed storms. The orientation and movement of such an idealized storm can be varied in order to maximize the catchment reaction. The spatial pattern is usually elliptically shaped with a ratio of 2.5:1 between the two axes of the ellipse (National Weather Service 1982). For the present study, a spatial pattern was generated that is roughly congruent with the considered catchment. The pattern was moved over the catchment in eight different directions. The pattern was slightly rotated in order to reproduce the motion of observed storms. The temporal distribution was set in a way that the bulk of the precipitation sum falls in the middle of the event. Orographic effects on the shape and on the motion of the idealized storm are neglected in this method.

The third precipitation distribution approach considered in this study is a Monte Carlo approach based on Felder and Weingartner (2016). This method entails generating numerous spatio-temporal distributions of the PMP using a Monte Carlo procedure. The PMP is temporally distributed over single time steps and spatially distributed over a number of sub-catchments. The distributions are semi-random, meaning that inter-dependencies between single sub-catchments and a certain temporal dependency are considered. In order to identify the distributions that maximize peak discharge, numerous generated precipitation patterns are iteratively tested in a hydrologic model. It is assumed that spatio-temporal precipitation distributions that maximize the peak discharge are the most relevant for further investigation (Felder and Weingartner, 2016). For the present study, 10^4 physically valid precipitation distributions were modelled. The 100 distributions that led to the highest peak discharges were identified and considered for further PMF modelling. Compared to the hyetograph method, this approach is less dependent on patterns and motions of observed storms, but it still ensures physical plausibility by considering temporal and spatial dependencies within the catchment.

The main differences among the applied precipitation distribution patterns are shown in Fig. 2. The uniformly distributed precipitation pattern does not show any variability in time and space. Such a distribution is not expected to occur in nature and therefore lacks in plausibility. The hyetograph method produces patterns that are elliptically shaped and have a certain temporal structure. The example shown in Fig. 2 is a storm moving from south to north that reaches the highest intensity above the central area of the catchment. Compared to a uniform distribution, the spatio-temporal precipitation patterns generated using the hyetograph method are more plausible because they better replicate observed patterns. The example of the Monte Carlo distribution shows a less smooth spatio-temporal distribution, and spatially the focus is more on a clear distinction between different meteorologically homogenous areas within the catchment than on a reconstruction of a storm motion. This approach best allows for a replication of observed spatio-temporal precipitation patterns and therefore leads to the most plausible distribution considered in this study.

3.2 Modelling approaches to determine PMF using PMP

This study considers three modelling approaches to evaluate the influence of model complexity on PMF estimation. A Unit Hydrograph-based model (in the following named UH-based model) was built in order to calculate the catchment reaction in a basic and straightforward way. For this purpose, Unit Hydrographs were calculated for three sub-catchments. Two sub-catchments cover the areas that drain into one of the two lakes indicated in Fig. 1; the third sub-catchment covers the rest of the area. The two lakes inside the catchment were handled as single linear storages. The runoff coefficient was set to 0.75, which corresponds to the upper limit of the reliable range according to the findings of Cerdan et al. (2004), Merz et al. (2006) and Norbiato et al. (2009). The model was calibrated using data from the highest observed flood event, which occurred in 2005, and validated for two relatively high observed flood events in 1999 and 2007. The resulting Nash-Sutcliffe criterion (NSE; Nash and Sutcliffe, 1970) is 0.88 (with a percent sum error of 4%) for the calibration event, and 0.61 (5%) and 0.88 (4%) for the two validation events.

The second modelling approach involves the use of a deterministic rainfall-runoff model. In this study, the hydrologic model PREVAH (hereafter referred to as the “hydrologic model”) was set up for the study area. PREVAH is a semi-distributed conceptual hydrologic model that is based on hydrological response units (HRUs). It provides a routing module to take into consideration the flow durations within a catchment, and a lake module to account for lake storage effects inside the catchment. A detailed model description is provided in Viviroli et al. (2009a). The applied model was parameterized using discharge time series from 2000 to 2010 (calibration) and 2011-2014 (validation). The resulting NSE is 0.92 for the calibration period and 0.81 for the validation period. The logarithmic derivative of the NSE, which is a more peak flow sensitive score (Viviroli et al. 2009b), amounts to 0.72 (calibration) and 0.67 (validation), which means that the calibrated model is able to replicate the catchment characteristics during flood events. This is supported by the fact that PREVAH has extensively been used in recent flood-related studies that were depicted in the same area

(FOEN 2008, FOEN 2009, Viviroli et al. 2009b, Viviroli et al. 2009c, Köplin et al. 2014, Viviroli and Seibert 2015) as well as in comparable catchments (Addor et al. 2011, Orth et al. 2015, Zappa et al. 2015).

The most sophisticated modelling approach entails a coupled hydrologic-hydrodynamic model (hereafter referred to as the "coupled model"). In order to apply it, the catchment was divided into several sub-catchments that drain into the main river. The reaction of the sub-catchments on the precipitation input was modelled using the hydrologic model PREVAH. The model was parameterized for each sub-catchment using a discharge time series from 2000 to 2010 (calibration) and 2011-2014 (validation). The main river and its surrounding flood-prone areas were modelled using the hydrodynamic model BASEMENT-ETH 1D (Vetsch et al. 2016). To incorporate retention and inundation processes that may occur outside the riverbed, the cross-sections were expanded to the flood-prone areas perpendicular to the flow direction. This relied on riverbed cross-section data acquired with a differential GPS system. The Swiss Federal Office for Environment provided these data. The cross-section information for flood-prone areas outside the riverbed was extracted from a DTM provided by the Canton of Bern. Its spatial resolution is 0.5 m with a vertical accuracy of ±0.2 m. The hydrodynamic model parameters (Strickler values, factor μ of the Poleni equation and contraction factors of pipes) were empirically derived by reconstructing observed flood events, with special focus on peak discharge and on flow duration along the main river.

The initial conditions in all three models were set in a way to represent average summer conditions in terms of antecedent soil moisture and initial storage levels. This ensured that the three modelling approaches were not influenced by varying initial conditions. For this study, the choice of average summer soil moisture conditions is reasonable because it corresponds with the season of the estimated PMP and because it is expected that differing model behaviour can be better identified under such conditions than under the assumption of fully saturated antecedent conditions.

3.3 Evaluation

As it is by definition not possible to validate a PMF estimation, evaluation is based on an assessment of the physical plausibility and reliability of an estimation and on an inter-comparison of the nine resulting estimations. For the evaluation, the result of the most reliable estimation is considered to be the reference estimation. The underlying assumption is that this combination of PMP and modelling approach leads to the best estimation. Regarding the spatio-temporal precipitation distribution, the Monte Carlo method best replicates observed storm patterns and is therefore considered to generate the most plausible distributions. Regarding the runoff modelling, the coupled hydrologic-hydrodynamic model best captures the processes that occur during a flood event, making it the most plausible runoff modelling approach. Therefore the estimation that results from the combination of the Monte Carlo precipitation distribution and the coupled hydrologic-hydrodynamic model is used as reference estimation. This reference estimation is used as a benchmark for the assessment of the eight other combinations.

4 RESULTS

The modelled hydrographs of all combinations of precipitation distribution methods and modelling approaches are shown in Fig. 3. The different methods of spatio-temporal PMP representation are shown in the rows. The different modelling approaches are shown in the columns.

The modelled hydrographs are highly varied in terms of magnitude of peak discharge, rising time and retention flow. The most straightforward option, namely the UH-based model fed with a uniformly distributed precipitation input, results in a peak discharge of 1160 $m^3 s^{-1}$. The hydrograph shows a relatively constant increase before peak discharge and a slightly slower decrease after peak discharge. The shape of the hydrograph directly reflects the model setup, i.e. the constitution and the arrangement of the Unit Hydrographs and the representation of the lakes. The UH-based model fed with hyetograph precipitation patterns results in strongly varying hydrographs. In this case, the magnitude of the peak discharge depends mainly on the storm direction. The highest peak discharge calculated using this method amounts to 1540 $m^3 s^{-1}$ and occurs when the generated storm moves in the direction of the catchment outlet from a region far away from the catchment outlet. In this particular catchment, this movement is from south-east to north-west. The precipitation patterns generated with the Monte Carlo approach fed into the UH-based model lead to the highest peak discharge of approximately 1680 $m^3 s^{-1}$. The UH-based model generally reacts linearly to incoming precipitation, with the exception of the effect of the two lakes.

The hydrologic model's reaction to a uniformly distributed PMP input is similar to the UH-based model's reaction, although when the hydrologic model is used the catchment reacts faster to heavy rainfall than when the UH-based model is used. This is mainly due to fact that the hydrologic model is able to differentiate between various precipitation intensities, meaning that extreme precipitation intensity leads to a relatively higher amount of direct runoff than a moderate one. Therefore, extreme precipitation, as applied in this study, reduces the modelled time to peak. In addition, the incorporation of various storages, e.g. soil moisture and groundwater storage, do affect the modelled catchment reaction when a hydrologic model is used. This effect lowers the modelled PMF by approximately 100 $m^3 s^{-1}$ to 1050 $m^3 s^{-1}$ compared to the PMF calculated with the UH-based model using the same precipitation distribution. Modelling the hyetograph distribution with the hydrologic model leads to similarly shaped hydrographs with the highest peak discharge at 1100 $m^3 s^{-1}$. The spatial structure of the precipitation pattern, an example of which is shown in Fig. 2, has a relatively small influence on the modelled catchment outflow. Regarding the hydrographs generated by the hydrologic model using the Monte Carlo-distributed precipitation, the modelled peak discharge is 1330 $m^3 s^{-1}$. As was the case using the UH-based model, the Monte Carlo precipitation distribution generated the highest peak discharge.

The application of a coupled model fed with the uniformly distributed precipitation leads to the lowest peak discharge of 750 $m^3 s^{-1}$, which is relatively close to the highest observed discharge of 613 $m^3 s^{-1}$. Remarkable are the distinct kinks in the hydrograph before and after peak discharge is reached. These reflect inundation and retention processes that are only considered in the coupled model. Using the coupled model, the precipitation distribution generated with the hyetograph method leads to a similar peak discharge of 790 $m^3 s^{-1}$. The modelled peak discharge is dependent on the design storm's direction of motion. Again, clear thresholds are visible, indicating the occurrence of inundation and retention processes. The application of the Monte Carlo-distributed precipitation patterns in the coupled model leads to a peak discharge of 1220 $m^3 s^{-1}$. The mentioned thresholds for inundation, retention and the emptying of retention areas (backflow into the river bed) are visible in all of the hydrographs. The Monte Carlo precipitation distribution leads to the highest peak discharge for this modelling approach as well.

The hydrographs that determine the PMF estimates, i.e. the hydrographs with the highest peak discharges, organized by applied modelling approach are shown in Fig. 4. Compared to the reference estimation (Monte Carlo precipitation distrubution fed into a coupled model), the UH-based model tends to overestimate the PMF. The hydrologic model shows less variation in the modelled peak discharges, and the peak discharges are relatively close to the reference peak discharge. In comparison to the reference estimation, the relatively short rising time and the smooth retention flows suggest that the behaviour of retentive storages is not well captured by the hydrologic model. The coupled model tends to result in a relatively low PMF estimation in case of low spatio-temporal variability of the precipitation input, although one of the three hydrographs shown in this plot is the reference estimation itself.

Figure 5 shows the influence of the spatio-temporal PMP representation on the hydrograph that defines the respective PMF estimation. A uniformly distributed PMP leads to PMF estimations below the reference scenario. The PMF estimations resulting from a PMP distributed using the hyetograph method are highly variable and lie below as well as above the reference scenario. The PMP distributed using a Monte Carlo-method generally leads to relatively high estimations. In comparison to the reference estimation, the method tends to overestimate the PMF when it is not applied with a model with corresponding spatial and temporal discretisation.

5 DISCUSSION

An overview on the PMF estimations that result from the combinations of PMP distribution approaches and modelling approaches is shown in Fig. 6. Two tendencies are remarkable. Regarding the spatio-temporal representation of the PMP, the application of a more complex method leads to a higher PMF estimation. Regarding the modelling approaches, the application of a more complex model generally leads to a lower PMF estimation.

5.1 Influence of the spatio-temporal PMP representation

The complexity of the spatio-temporal PMP distribution coincides with the height of the corresponding PMF estimation. A uniform PMP distribution in space and time does not maximize the catchment reaction, which aligns with the findings of Seo et al. (2012). Compared to the reference PMF estimation, the uniform PMP distribution method leads to a significant underestimation of the PMF. Moreover, such a distribution lacks consistency with observed storm patterns. The value of a uniform distribution lies in its relatively simple and efficient generation procedure, as well as in the simple application of the pattern in any model. The second PMP distribution method under consideration, the hyetograph method, demonstrates a higher spatio-temporal PMP variability than the uniform PMP distribution method. The hyetograph method generates arrangements that lead to both lower and higher peak discharges than the uniform distribution does. As only the highest peak discharge defines the PMF, the hyetograph distribution leads to a higher PMF estimation than the uniform distribution. The highest degree of variability in space and time, as well as the highest number of scenarios, is generated with the Monte Carlo method. This allows for the consideration of more possible distributions that could maximize the catchment reaction, leading to the highest PMF estimations.

These findings can be generalized to a certain degree. However, the specific influence of the spatio-temporal precipitation distribution on the PMF estimation is catchment-specific. Recent studies have shown that the influence of rainfall variability on flood response depends on catchment size, catchment characteristics and runoff generation processes

(Nicótina et al. 2008, Adams et al. 2012, Lobligeois et al. 2014, Paschalis et al. 2014, Emmanuel et al. 2015). These effects may accentuate or mask the general implications of the choice of a spatio-temporal PMP representation that are described above. As the discharge-maximizing PMP distribution is not known *a priori*, it is reasonable to incorporate as many and as varying spatio-temporal PMP distributions as the available data allow, provided that the distributions are physically plausible. This reduces the chance of missing a discharge-maximizing spatio-temporal distribution.

5.2 Influence of the modelling approach

The ways that the models differently consider and represent physical processes explain why increased model complexity lowers PMF estimation. The UH-based model converts the incoming precipitation relatively directly to catchment outflow. Besides the effect of the lakes, which is considered in the UH-model applied in this study, the model simulates no additional processes that could lower peak discharge. In contrast, the hydrologic model deterministically incorporates retentive factors e.g. soil moisture storages, groundwater storages and interflow storages. Regarding extreme precipitation inputs, these storages have retentive effects that, in sum, reduce peak discharge at the catchment outflow. The coupled model additionally captures the most relevant retention processes resulting from inundation and the storage of water masses on floodplains that are not considered in the hydrologic model. This has an additional effect of lowering peak discharge. In accordance with Grayson and Blöschl (2011), Gupta et al. (2008), Hrachowitz et al. (2014) and Pfannerstill et al. (2015), it can be stated that an increasing model complexity also increases the representation of physical processes. This more accurate representation of physical processes dampens the modelled peak discharge and therefore the PMF estimation.

Although the different modelling approaches lead to systematically different estimations, the magnitude of the difference attributable to the modelling approach is expected to be catchment specific. This is due to varying decisive flood-triggering processes (Paschalis et al. 2014), varying channel network topology (Moussa 2008) and the varying presence of lakes and artificial structures. Besides the actual differences in catchment behaviour, the representation of the mentioned effects in a model depends on the model's structure (Vansteenkiste et al. 2014).

As is the case with the peak-discharge-maximizing spatio-temporal precipitation distributions, the decisive flood-triggering and peak-discharge-dampening processes are also not known *a priori*. This calls for the application of a model that incorporates as many potentially decisive processes as possible, hence for the appliction of a model as sophisticated as the available data allow for.

5.3 Combined influence

The modelling approach and the spatio-temporal PMP representation have a strong influence on the resulting PMF estimation. Regarding the precipitation distribution approach, an increasing complexity generally increases the resulting PMF estimation. The opposite can be stated for the runoff modelling method; an increasing complexity generally decreases the resulting PMF estimation. The superposition of these two opposing effects leads to consistent estimations that result from a combination of methods with a similar degree of complexity. The use of a basic UH-based model fed with a uniformly distributed precipitation, as well as the use of a hydrologic model fed with hyetograph patterns, leads to a PMF estimation that is close to the reference estimation. The choices of a modelling approach and a spatio-temporal PMP representation approach should be coordinated in order to avoid adverse combinations. Particularly the use of a highly sophisticated model with a relatively coarse spatio-temporal PMP representation should be avoided, as such an application tends to underestimate the PMF compared to the reference estimation. In contrast, the use of a basic and straightforward model fed with highly variable precipitation patterns tends to overestimate the PMF compared to the reference estimation and should therefore also be avoided.

6 CONCLUSIONS

Three different spatio-temporal PMP representations were fed into three different models in order to estimate the PMF for an alpine catchment. The nine resulting PMF estimations vary distinctively. One main reason for the differences in the PMF estimations is the varying degree of spatio-temporal variability of the PMP representations. The PMF estimation increases with increasing variability in the spatio-temporal distribution of the precipitation input. The second main reason for the differences in the PMF estimations is the varying representation of physical processes in the applied modelling approaches. The PMF estimation decreases with increasing model complexity due to the increasing number of physical processes that are captured by the applied model. The results of this study show that the choice of spatio-temporal PMP representation and the choice of modelling approach should be carried out in a balanced way such that they are compatible with each other.

The PMP distribution approach and the PMF modelling approach should be chosen based on a study's aim and on the availability of data and expertise, provided the modelling approach and the spatio-temporal PMP representation are consistent and of similar complexity. The application of a basic UH-based model fed with a uniformly distributed PMP enables a rough PMF estimation. The use of a hydrologic model for PMF estimation fed with hyetograph PMP patterns can be seen as a compromise between degree of detail and computational efficiency. It can lead to reasonable results, provided the precipitation distribution approach and the modelling approach are of similar complexity. The application of such a method is recommended in cases when a sophisticated estimation is not doable, e.g. because of limitations in data availability, insufficient computational resources or time constraints. However, important processes like floodplain retention are still neglected using both of the aforementioned options. Thus, in cases where highly reliable estimation is required, e.g. for insurance purposes or for the planning of sensitive infrastructure, a sophisticated estimation approach is recommended, as decisive physical processes can influence the result remarkably. PMF estimation is of high relevance in most cases; therefore it is reasonable to strive for the most sophisticated modelling approach. In all cases, the mutual influence of the complexity of precipitation patterns and the complexity of the applied model must be accounted for to avoid a notable under- or overestimation of the PMF.

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Figure captions

Fig. 1: The Aare catchment located in central Europe. Four main torrents in the mountainous southern part of the catchment drain into the two lakes. Widespread flood-prone areas are situated downstream of the lower lake.

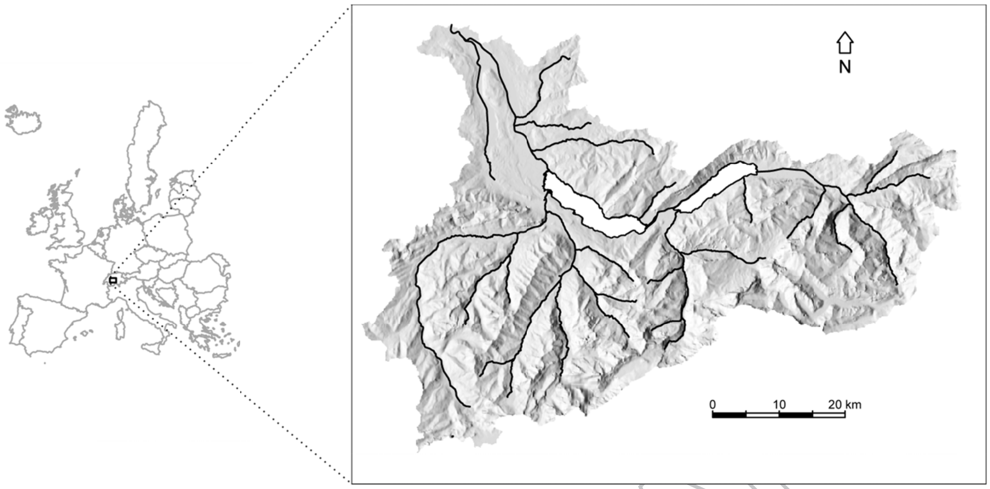

Fig. 2: Examples of spatial and temporal patterns that result from the application of different PMP representation methods.

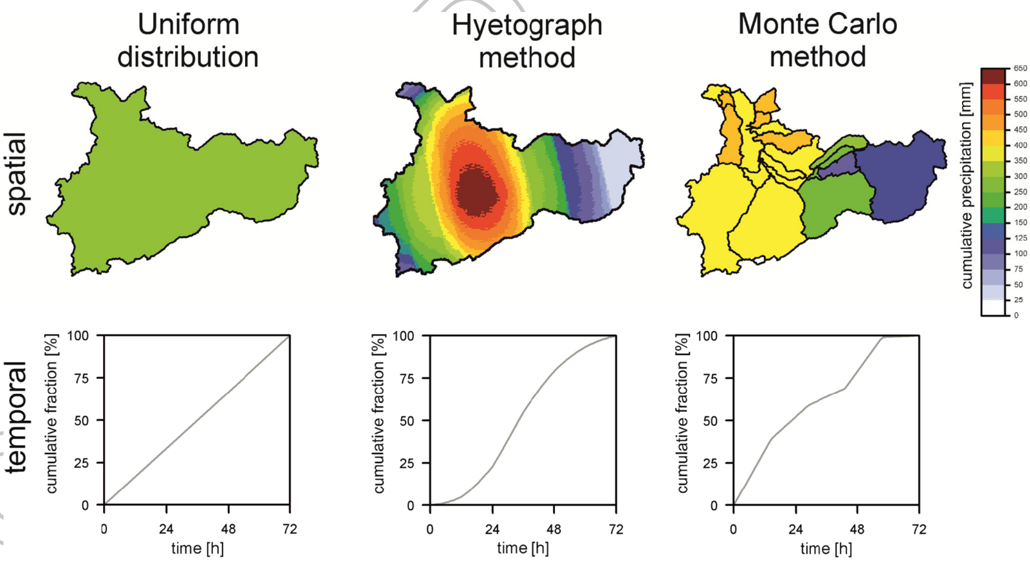

Fig. 3: Resulting hydrographs of all combinations of the three spatio-temporal PMP representation approaches and the three applied modelling approaches at the outlet of the study area. The highest peak discharge of each combination is considered to be the corresponding PMF estimate.

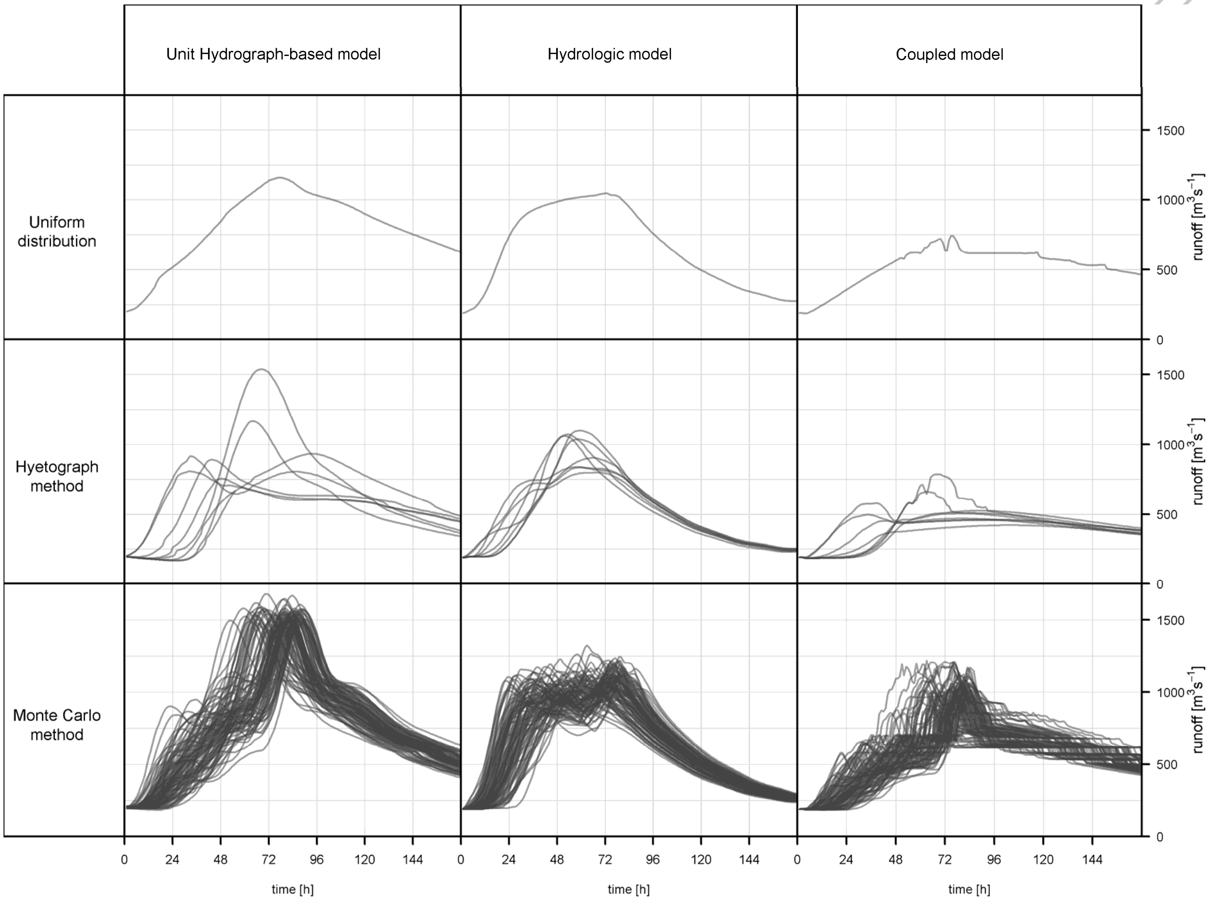

Fig. 4: In grey, the highest hydrographs generated by the method combinations, sorted by modelling approach. The peaks of the hydrographs indicate the corresponding PMFs. The differences in the hydrographs are attributable to the varying spatio-temporal PMP distributions applied. The bold black line represents the reference hydrograph (Monte Carlo PMP distribution, coupled model).

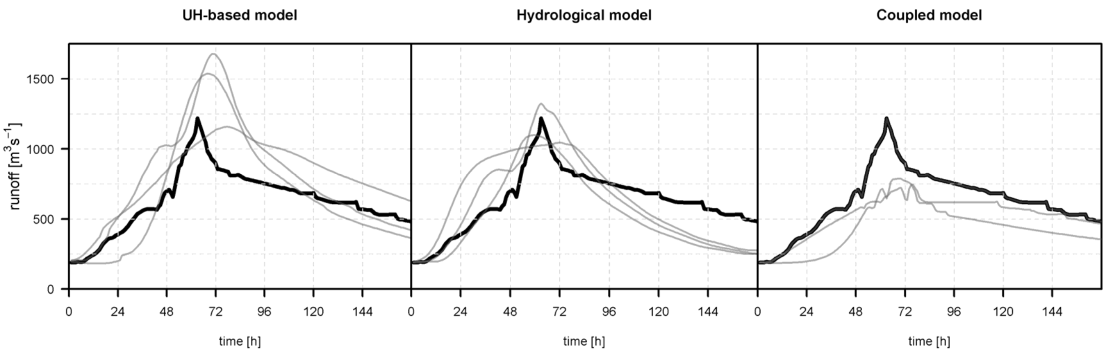

Fig. 5: In grey, the highest hydrographs generated by the method combinations, sorted by spatio-temporal PMP representation. The peaks of the hydrographs indicate the corresponding PMFs. The differences in the hydrographs are attributable to the varying modelling approaches applied. The bold black line represents the reference hydrograph (Monte Carlo PMP distribution, coupled model).

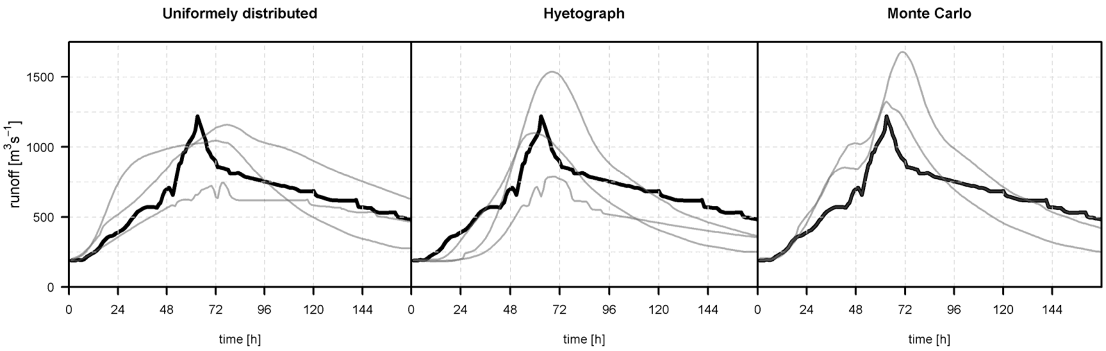

Fig. 6: Resulting PMF estimates of all combinations of the three spatio-temporal PMP representations and the three applied modelling approaches.